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RESEARCH MEMORANDUM

PRELIMINARY EVALUATION OF THE AIR AND FUEL SPECIFIC-IMPULSE CHARACTERISTICS OF SEVERAL POTENTIAL RAM-JET FUELS

II - MAGNESIUM AND MAGNESIUM - OCTENE-1 SLURRIES

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

A preliminary analytical evaluation of the air and fuel specific-impulse characteristics of magnesium and magnesium - octene-1 slurries was made.

Adiabatic combustion flame temperature, air specific impulse, and fuel-weight specific impulse are given for each fuel. The air- and fuel-weight specific-impulse data for octene-1, which was taken as representative of hydrocarbon performance, are presented for comparison.

The combustion flame temperatures available with magnesium and magnesium - octene-1 slurries are greater than those for octene-1. The air specific impulse, or thrust, available for magnesium and for magnesium - octene-1 slurries exceeds that available for octene-1. Ram-jet combustor operation with magnesium hydrocarbon slurries offers a means of improving the fuel-weight specific impulse attainable with magnesium alone and of increasing the limiting air specific impulse attainable with hydrocarbon alone.

Under the conditions considered in the calculations, aluminum gives a better fuel-weight specific impulse than magnesium for all air-specific-impulse values less than 185; for air specific-impulse values greater than 185, magnesium apparently gives superior fuel-weight specific-impulse values. Under the conditions considered in the calculations, magnesium - octene-1 slurries are roughly equal, or superior, to aluminum - octene-1 slurries with respect to fuel-weight specific impulse at a fixed air specific impulse.

INTRODUCTION

An analytical investigation is being conducted at the NACA Lewis laboratory to determine the air and fuel specific-impulse characteristics of several potential ram-jet fuels. This analytical investigation is a part of a larger program to explore ram-jet fuel potentialities experimentally and analytically. Fuels being considered in the analytical investigation include: boron, diborane, pentaborane, hydrogen, α-methylnaphthalene, octene-1 (taken as representative of aviation-gasoline performance), graphite carbon, and slurries of boron, magnesium, and aluminum, in octene-1. Data on the air and fuel specific-impulse characteristics for octene-1, aluminum, and aluminum - octene-1 slurries are presented in reference 1. The air specific impulse is a measure of the potential thrust, whereas the fuel-weight specific impulse is a measure of the length of time a pound of fuel will maintain the air specific impulse. The fuel specific impulse is a measure of the fuel economy.

The practical utilization of solid metals as fuels for other than short-range ram jets presents considerable fuel transport and injection problems. The use of fluidized metal-hydrocarbon slurries offers one possible way of achieving metal-fuel benefits with an apparent minimum alteration of current liquid-fuel storage, pumping, and injection apparatus and techniques.

Magnesium offers possible advantages over aluminum as a potential ram-jet fuel. The heat of combustion per pound of air for magnesium is greater than for aluminum. Magnesium is more chemically reactive than aluminum; this suggests possible advantages of combustion stability. One of the commercial manufacturing methods (reference 2) produces magnesium in a finely divided state which may prove to be suitable for use in hydrocarbon slurries.

The physical properties of the metal oxide formed in combustion are important with regard to the formation of deposits in the combustor and nozzle. Aluminum sesquioxide undergoes a solid-liquid phase transition at temperatures sufficiently low to make deposits an operational problem (reference 3). The magnesium oxide solid-liquid phase transition takes place at a considerably higher temperature than the aluminum sesquioxide transition. As a consequence, less difficulty due to oxide deposits might be anticipated for magnesium when used as a ram-jet fuel.

The present report gives data for magnesium and for magnesium - octene-1 slurries on:

2145 (a) Adiabatic combustion flame temperature as a function of equivalence ratio

(b) Air specific impulse as a function of equivalence ratio

(c) Fuel-weight specific impulse as a function of fuel equivalence ratio

(d) Fuel-weight specific impulse as a function of air specific impulse

THERMODYNAMIC DATA AND ANALYTICAL METHOD

Thermodynamic data. - Thermodynamic data for the constituents, with exceptions indicated below, are taken from reference 4. An empirical equation (given in reference 5) for the heat capacity of magnesium oxide was used to obtain tabulated values of enthalpy, entropy, and heat capacity. The heat of formation of magnesium oxide is also taken from reference 5; the standard-state entropy of magnesium oxide is taken from reference 6. Thermodynamic data for the vapor pressure of magnesium oxide at elevated temperatures, the boiling point temperature, the latent heat of vaporization of magnesium oxide, and the equilibrium constants for the dissociation of magnesium oxide are of such a nature that special assumptions had to be made in the analytical method.

Analytical method. - The analytical method employed is presented in reference 1; the same method was used for magnesium and magnesium - octene-1 slurries as was used for aluminum and for aluminum - octene-1 slurries. The empirical heat-capacity equation for magnesium oxide is valid up to 3800° R with an accuracy of ± 2 percent; it was extrapolated to about 5800° R. Suitable vapor-pressure data for magnesium oxide as well as equilibrium data with magnesium and oxygen are not available. Consequently, throughout the calculations, magnesium oxide was considered a nondissociating condensed phase without significant vapor pressure. No attempt was made to extend the calculations to higher temperatures and air-specific-impulse values because of these limitations.

The constituents considered to be present when magnesium was used as the sole fuel are: solid magnesium oxide, nitrogen, oxygen, nitric oxide, atomic nitrogen, and atomic oxygen. The constituents considered when magnesium - octene-1 slurries were used are: solid magnesium oxide, carbon dioxide, nitric oxide, water, oxygen, hydrogen, nitrogen, carbon monoxide, hydroxyl radical, atomic hydrogen, atomic nitrogen, and atomic oxygen. 2145

Combustor inlet-air conditions are taken as 560° R and a pressure of 2 atmospheres throughout the analysis. The terms "fuel equivalence ratio and stoichiometric fuel fraction" are based on the oxygen available in the air and are used interchangeably.

RESULTS AND DISCUSSION

Temperature. - The adiabatic constant-pressure combustion temperature and the nozzle-exit gas temperature for magnesium and for magnesium - octene-1 slurries are presented in figures 1(a) and 1(b), respectively. At a stoichiometric fraction of 0.5 and an inlet-air temperature of 560° R, the adiabatic combustion temperature is 5500° R for magnesium. For the magnesium - octene-1 slurry at a total stoichiometric fuel fraction of 1.0 and a magnesium stoichiometric fuel fraction of 0.5, the adiabatic combustion temperature is 5720° R.

Air specific impulse. - At a fixed total fuel equivalence ratio of 1.0 for magnesium - octene-1 slurries, the air specific impulse varies from 170.4 ((lb)(sec)/lb air) at a magnesium equivalence ratio of 0 to 208 ((lb)(sec)/lb air) at a magnesium equivalence ratio of 0.5 as is represented in figure 2. It is not anticipated that this approximately linear variation of air specific impulse with magnesium equivalence ratio would hold up to a magnesium equivalence ratio of 1.0. The weight percent of magnesium in the slurry is shown as an auxiliary scale.

The variation of air specific impulse with stoichiometric magnesium fraction is presented in figure 3. The air specific impulse varies nonlinearly from 109 at a magnesium equivalence ratio of 0.1 to 191 at an equivalence ratio of 0.5. The dashed octene-1 curve, taken as representative of aviation-gasoline performance, is shown in this figure as a reference standard. At the stoichiometric point, data for the air specific impulse of magnesium - octene-1 slurries at the 0.1, 0.3, and 0.5 magnesium equivalence fractions taken from figure 2 are shown in figure 3. This figure suggests a manner of interpolating or extrapolating the data to conditions not covered in the calculations.

Fuel-weight specific impulse. - The variation of fuel-weight specific impulse with magnesium equivalence ratio is presented in figure 4. In figure 5 is shown the variation of fuel-weight specific impulse with stoichiometric fraction of magnesium in a magnesium - octene-1 slurry
2145 when the total stoichiometric fuel fraction is fixed at 1.0.

Relation between air and fuel specific impulse. - Figure 6 presents the variation of fuel-weight specific impulse with air specific impulse for magnesium. These data were obtained by cross plotting the data for fuel- and air-specific-impulse variation with stoichiometric fuel fraction. The curves for octene-1 and for aluminum are shown also. At a fixed air specific impulse below 172 [(lb)(sec)/lb air], octene-1 gives a fuel specific impulse superior to magnesium. Magnesium, however, permits the attainment of higher air-specific-impulse values than octene-1. For air-specific-impulse values below about 185, aluminum gives fuel-specific-impulse values superior to magnesium; above this value the inverse is apparently true.

The variation of fuel-weight specific impulse with air specific impulse for magnesium - octene-1 slurries at a fixed total stoichiometric fuel fraction of 1.0 is presented in figure 7. The aluminum - octene-1 dotted curve is shown for comparison. The magnesium - octene-1 slurries, under these conditions, are roughly equal, or superior, to aluminum - octene-1 slurries with regard to the value of fuel-weight specific impulse at a fixed air specific impulse.

Data for octene-1, magnesium, and magnesium - octene-1 slurries previously shown in figures 6 and 7 are represented on a common scale in figure 8.

SUMMARY OF RESULTS

For the conditions of this preliminary analysis, the following conclusions may be drawn:

1. Magnesium is capable of producing higher combustion flame temperatures than octene-1. Magnesium used as a ram-jet fuel is capable of producing a higher limiting air specific impulse than octene-1. Where ram-jet combustion operation is feasible at a given air specific impulse with octene-1 and with magnesium, octene-1 has a higher fuel-weight specific impulse than magnesium.

2. Magnesium-octene-1 (or magnesium-hydrocarbon) slurries offer a means of increasing the limiting air specific impulse available with octene-1 (hydrocarbon fuels). With magnesium - octene-1 slurries a higher fuel-weight specific impulse is possible than when ram-jet operation is achieved at the same air specific impulse with magnesium alone. 2145

3. Under the conditions considered in these calculations, aluminum gives a fuel-weight specific impulse superior to magnesium for all air specific-impulse values less than about 185 [(lb)(sec)/lb air]; above air-specific-impulse values of 185 [(lb)(sec)/lb air], the inverse is apparently true.

4. Under the conditions considered in these calculations, magnesium - octene-1 slurries are roughly equal, or superior, to aluminum - octene-1 slurries with respect to fuel-weight specific impulse at a fixed air specific impulse.

5. Additional thermodynamic data for magnesium oxide at elevated temperatures are required to extend this analysis to higher temperatures and higher air-specific-impulse values.

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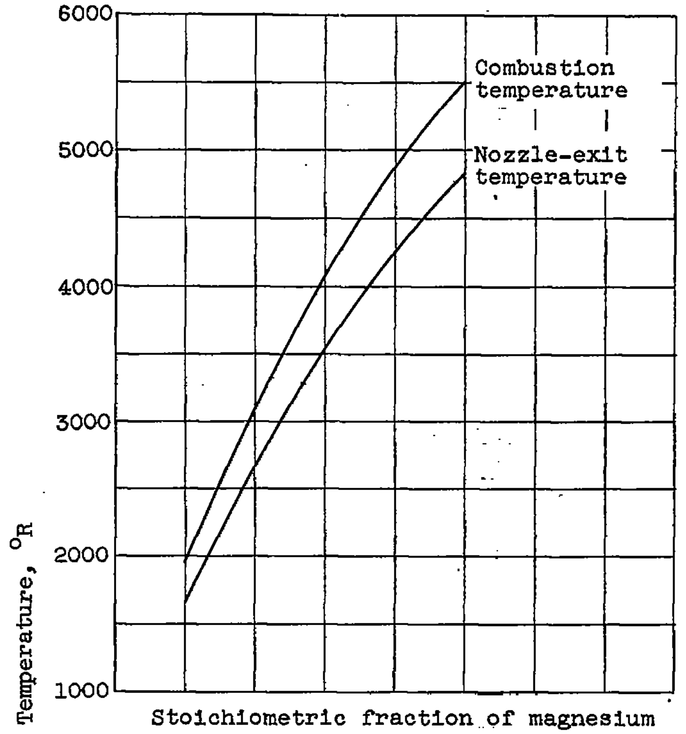
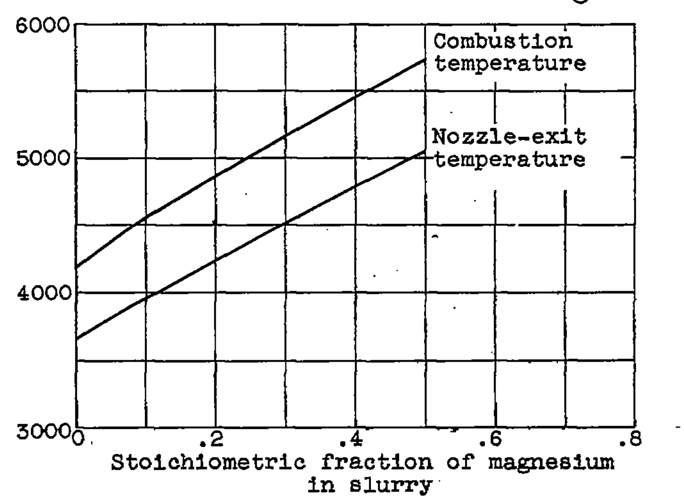


(a) Fuel, magnesium.



(b) Fuel, magnesium in slurry; stoichiometric fraction of magnesium plus octene-1 fixed at 1.0.

Figure 1. - Theoretical combustion- and nozzle-exit temperature variation with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres; expansion ratio, 2.0.

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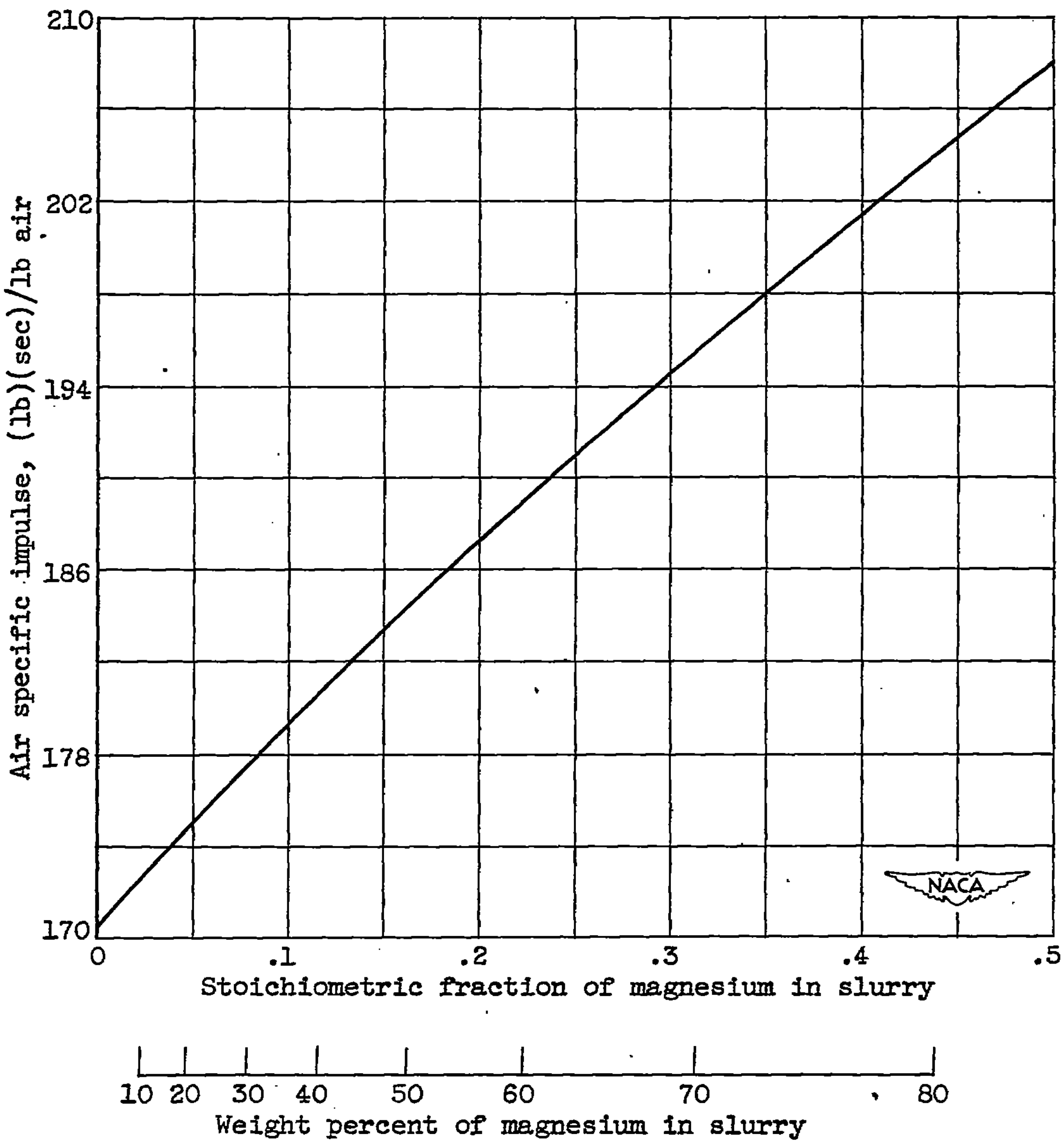

Figure 2. - Variation of air specific impulse with stoichiometric fraction of magnesium in slurry. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. Stoichiometric fraction of magnesium plus octene-1 fixed at 1.0.

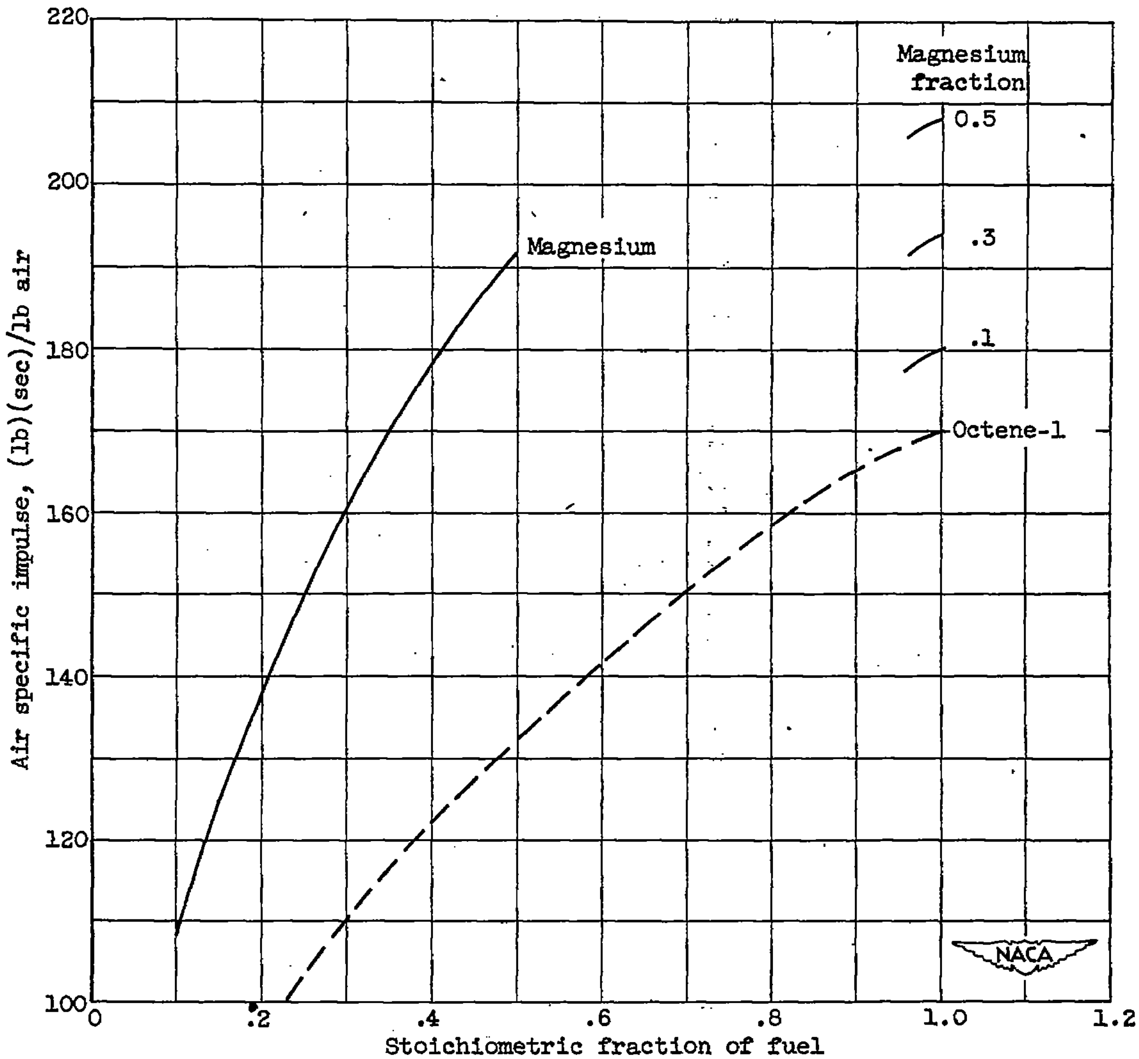

Figure 3. - Variation of air specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

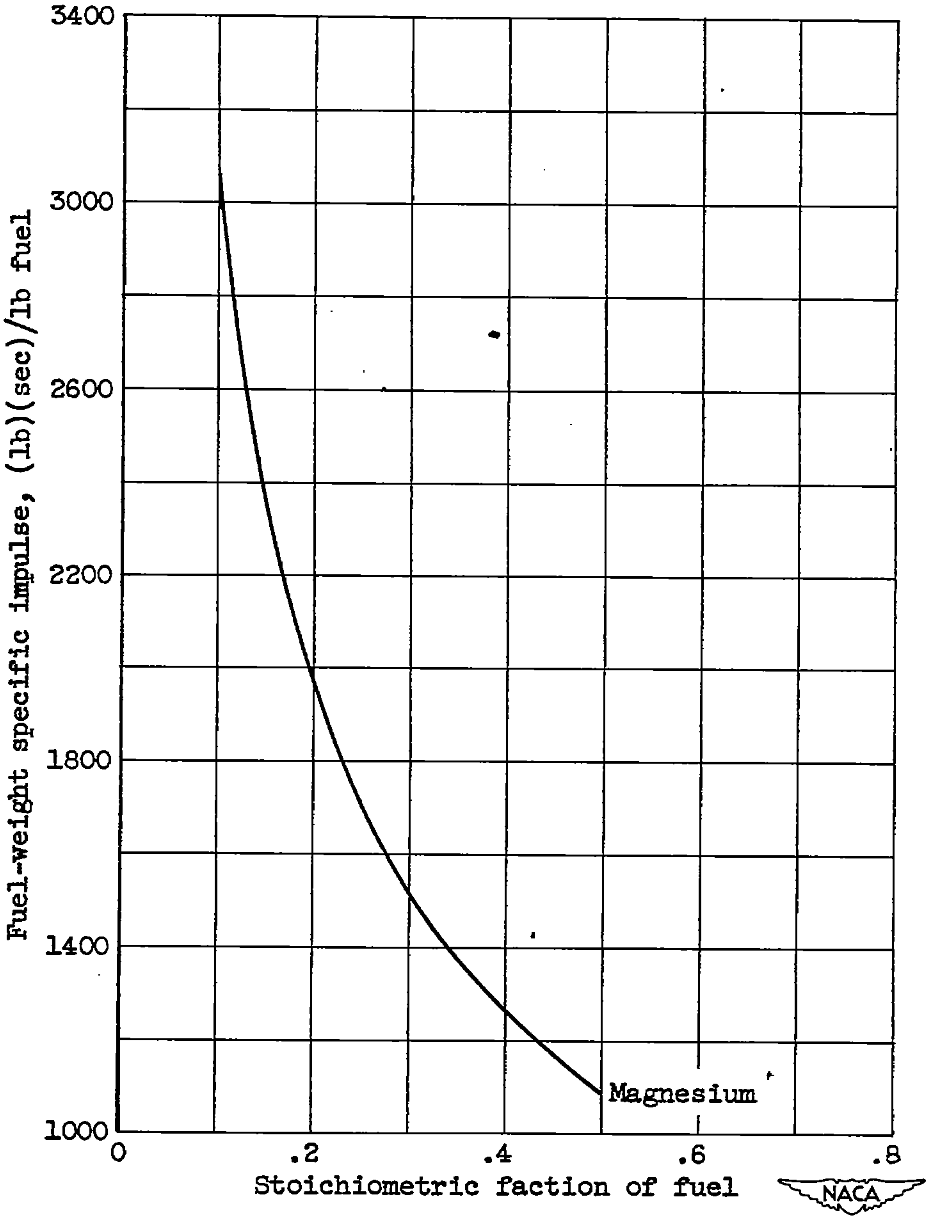

Figure 4. - Variation of fuel-weight specific impulse with stoichiometric fraction of fuel. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres.

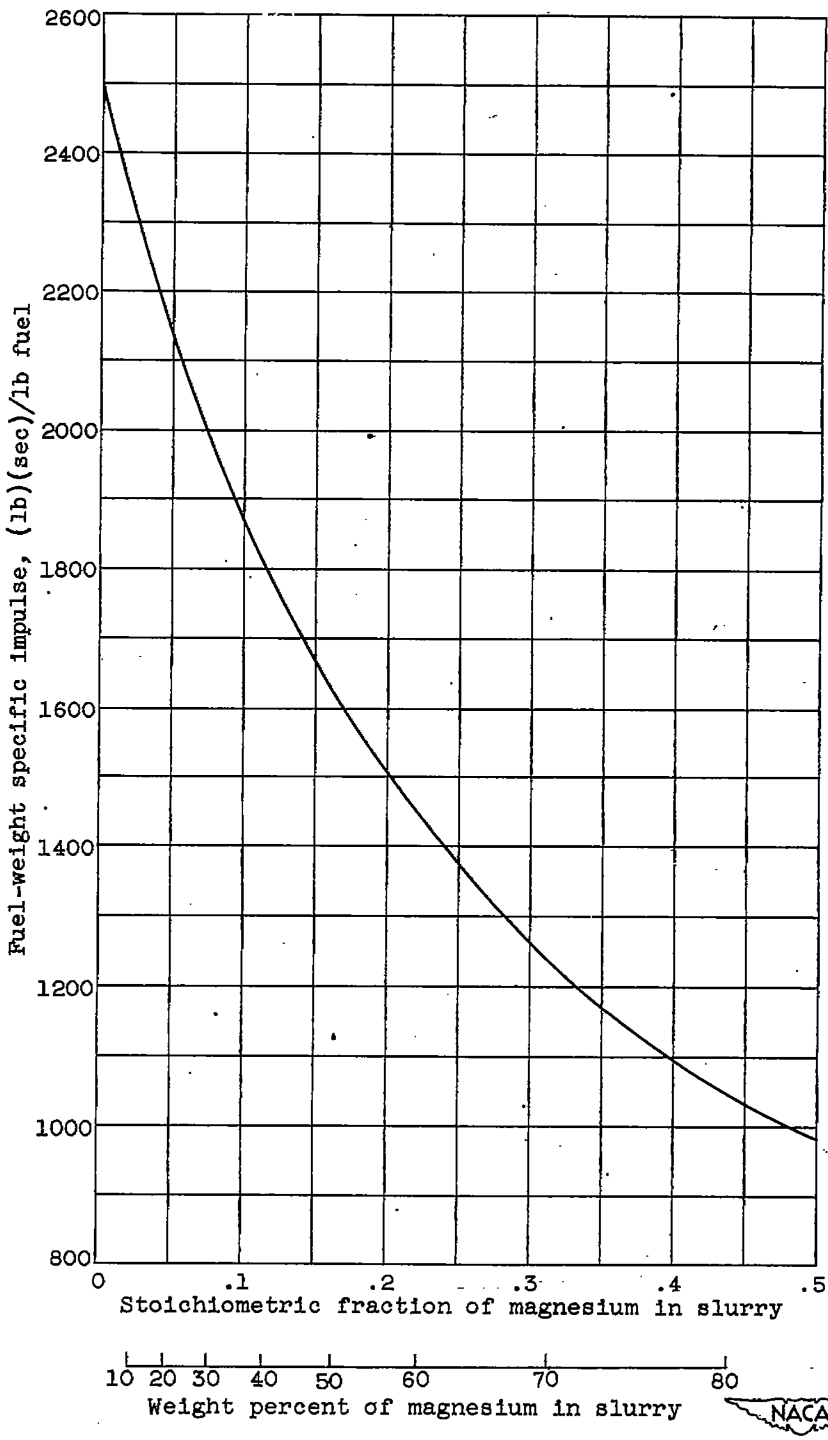

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Figure 5. - Variation of fuel-weight specific impulse with stoichiometric fraction of magnesium in slurry. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. Stoichiometric fraction of magnesium plus octene-1 fixed at 1.0.

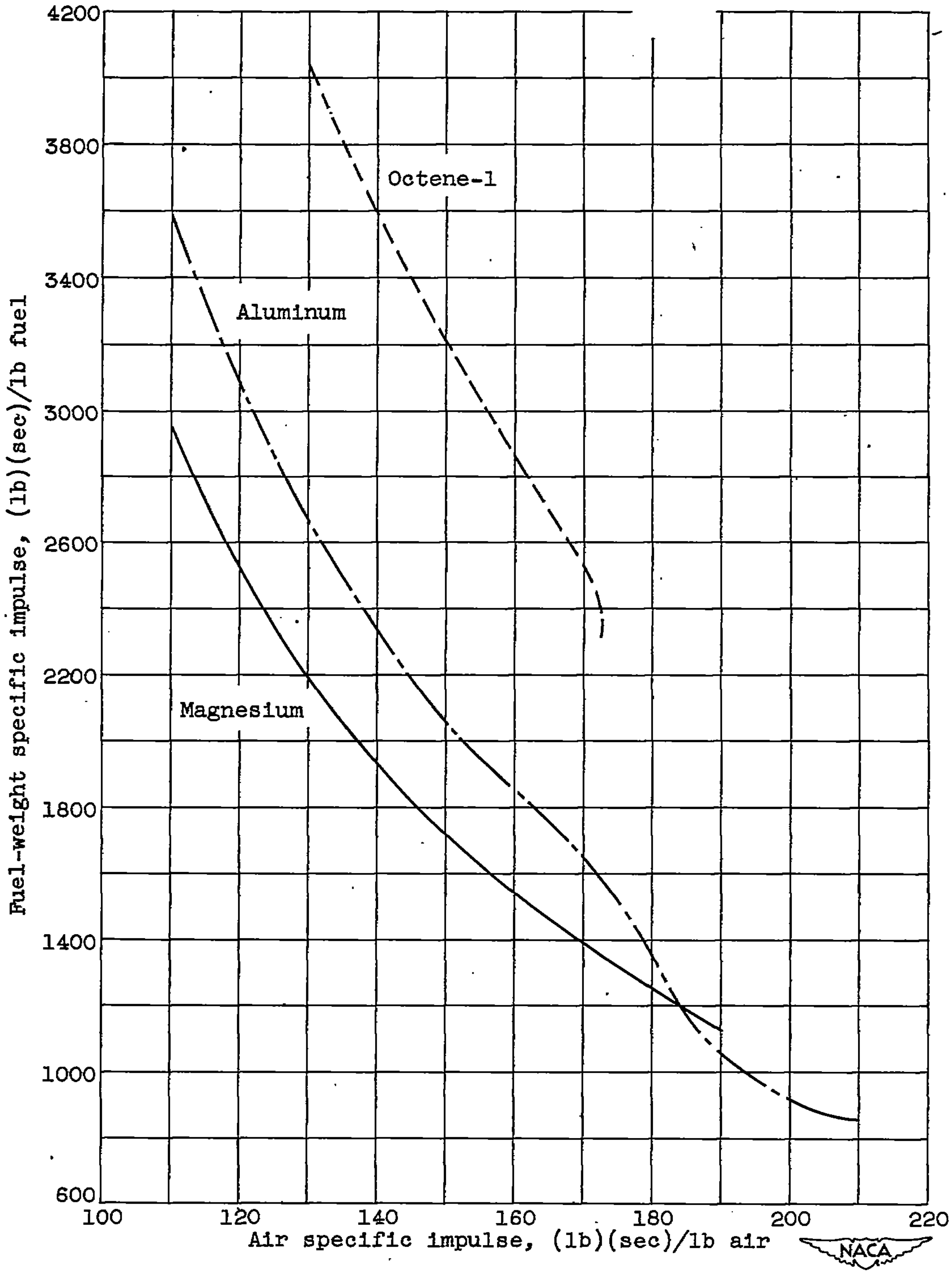

Figure 6. - Variation of fuel-weight specific impulse with air specific impulse for aluminum, octene-1, and magnesium. Combustor inlet-air temperature, 560 R; inlet-air pressure, 2 atmospheres.

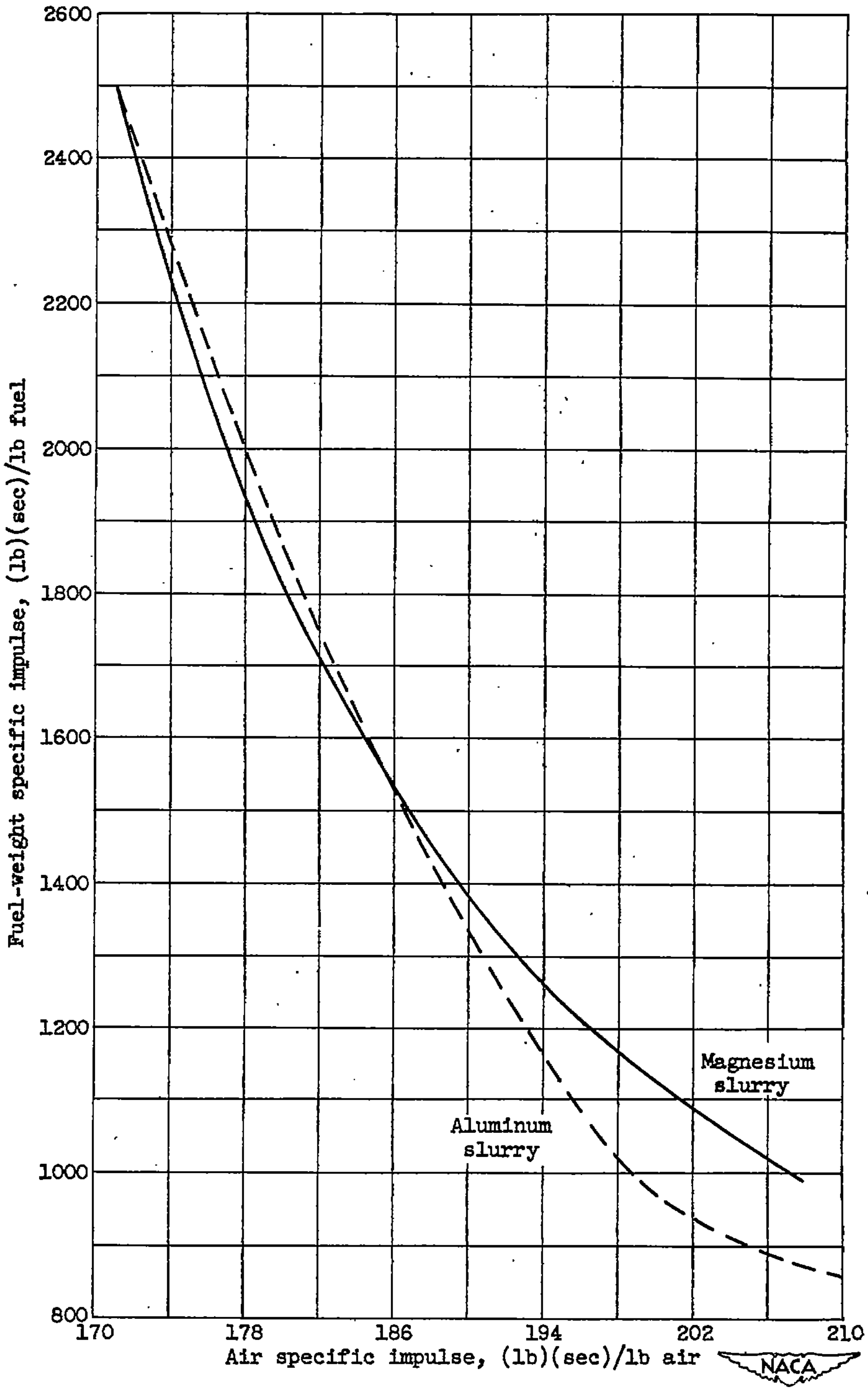

Figure 7. - Variation of fuel-weight specific impulse with air specific impulse for magnesium slurry in octene-1. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. Stoichiometric fraction of magnesium plus octene-1 fixed at 1.0.

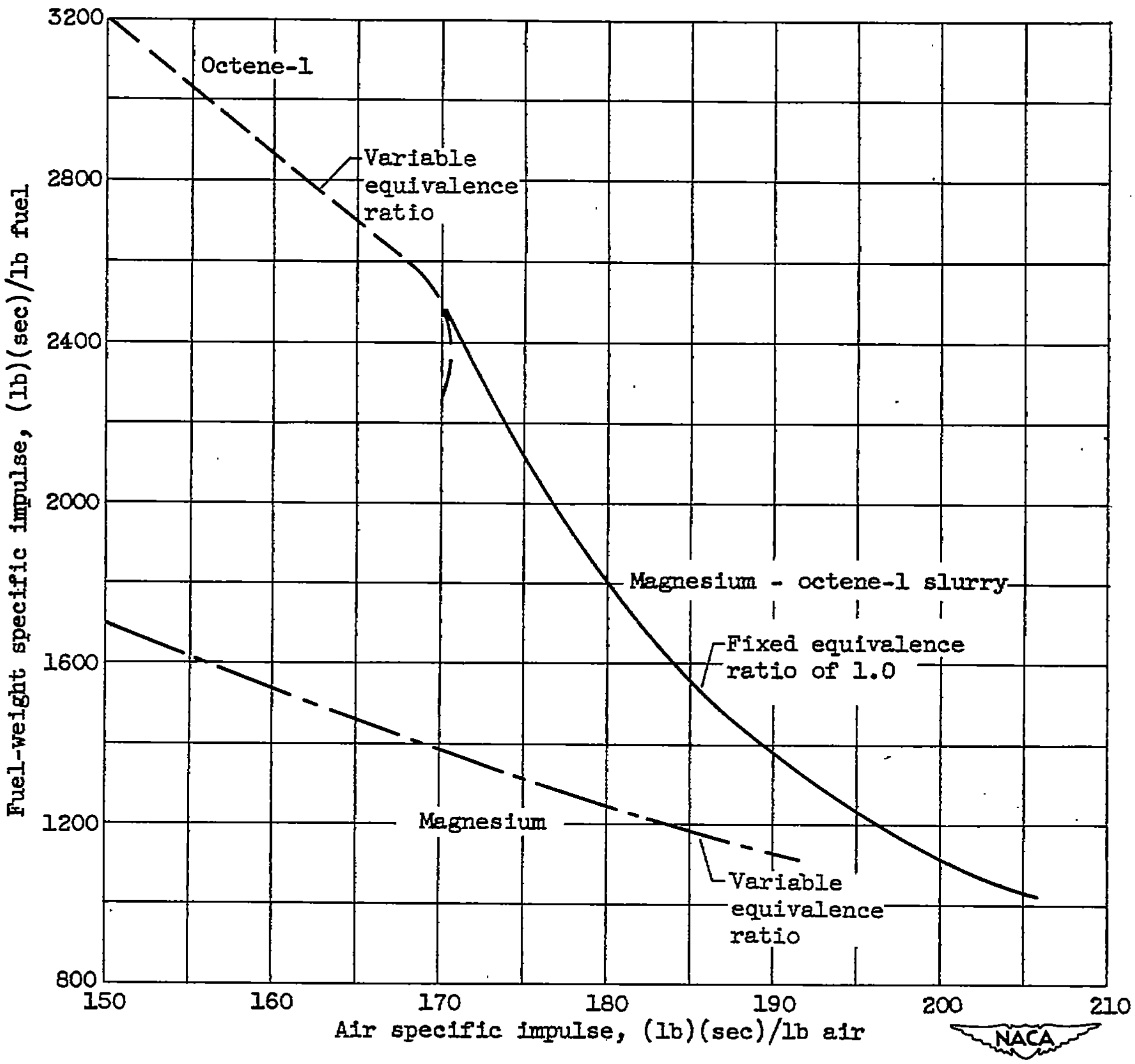

Figure 8. - Comparison of air- and fuel-specific impulse characteristics for octene-1, magnesium, and magnesium - octene-1 slurries.